

Different mechanisms for efficient optical transmission through bilayered subwavelength patterned metal films

Jian Wang¹, Yong Zeng^{2*}, Xiaoshuang Chen^{1†}, Wei Lu^{1‡}, Jerome V. Moloney²

1. *National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Science, 200083 Shanghai, China*

2. *Arizona Center for mathematical Sciences, University of Arizona, Tucson, Arizona 85721*

Light transmission through bilayered thin metal films perforated with subwavelength hole arrays are numerically studied based on a full-vector finite-difference time-domain approach. A variety of transmission peaks originating from different physical mechanisms are observed. In addition to the direct tunnelling and Fabry-Pérot resonances, generally possessed by idealized bilayered dielectric slabs, the near-field localized plasmon polaritons also play important roles. They not only influence the direct tunnelling in a destructive or constructive way, the interactions between these localized plasmon polaritons on different metal films also result in additional channels which transfer optical energy effectively.

PACS numbers: 78.20.Bh

Subwavelength hole arrays in metallic thin films have received considerable attention recently after the experimental findings of Ebbesen in 1998 [1]. The transmission of light through such a nanostructured system has been shown to be extraordinarily efficient at specific wavelengths longer than the array period [2, 3, 4, 5]. Because of many potential applications such as near-field microscopy and flat-panel displays, the Ebbesen's work has sparked a wealth of research activities both experimentally [6, 7, 8, 9, 10] and theoretically [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21]. Moreover, various aspects of the single-layer structure have been studied to exploit the underlying physical mechanisms, including the arrangement of the subwavelength holes [1, 6], thickness of the metal film [7, 17], polarization of the incident light [8], hole shape [8] and symmetry of the whole structure [20].

A wealth of reasonable explanations about the Ebbesen's experiments have been presented such as the formation of localized waveguide resonances [22] and shape resonances, as well as the interference of diffracted evanescent waves [3, 4, 5]. Among them the excitation of localized plasmon polaritons (LPPs) is widely believed to play an important role [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21]. LPPs are the oscillations of conduction electrons inside the metal forced by the external electromagnetic waves. Because of its pure imaginary wave vector in the normal-to-the-interface direction, it is therefore a surface wave whose amplitude decays exponentially with increasing distance into each medium from the interface. This field confinement leads to the enhancement of the electromagnetic field at the interface, which in turn leads to the extraordinary sensitive dependence of the LPPs properties on the surrounding dielectric conditions [23]. In this work, instead of studying a single-layer struc-

tured metal film, we investigate bilayered films with variable layer separations. We will show that at least three kinds of physical mechanisms contribute to the efficient light transmission, including the direct tunnelling, Fabry-Pérot resonances, and additional channels formed by the interaction between the LPPs on different films.

We first consider an idealized structure consisting of two identical dielectric slabs (with a real refractive index n_2 and thickness d) embedded into a homogeneous medium (with a real refractive index n_1). Under normal incidence with wavelength λ , the transmission intensity of an individual dielectric slab is written

$$T_s = \left[1 + \sin^2 \phi \left(\frac{n_1^2 - n_2^2}{2n_1 n_2} \right)^2 \right]^{-1}, \quad (1)$$

with $\phi = 2\pi n_2 d / \lambda$. This equation immediately suggests that (1) light propagates through a homogeneous media (assuming $n_1 = n_2$) without reflection; (2) the slab thickness d influences the optical transmission remarkably. More specifically, $d = n\lambda/2n_2$ results in maximal transmission while $d = (n + 1/2)\lambda/2n_2$ leads to maximal reflection, with n being an integer. For the idealized double-layer structure with s being the layer separation, the corresponding transmission intensity is

$$T_d = \left\{ \frac{(2 - T_s)^2}{T_s^2} + \frac{(T_s - 1)[2 - 2\cos(\alpha + \varphi)]}{T_s^2} \right\}^{-1} \quad (2)$$

where α stands for the phase of the complex transmission coefficient of the single slab, and $\varphi = 2\pi n_1 s / \lambda$. Evidently, $T_d = 1$ as long as $T_s = 1$, in other words, an efficient transmission of single layer also leads to an efficient transmission of bilayered structure. We denote this mechanism as direct tunnelling since it only relates to the optical properties of single-layer slab. Eqs.(2) further suggests T_d is strongly sensitive to φ and therefore the layer separation s , that is, T_d oscillates between 1 (with $\cos(\alpha + \varphi) = -1$) and $T_s^2/(2 - T_s)^2$ (with $\cos(\alpha + \varphi) = 1$).

*The first and second author contributes equally to this article.

†xschen@mail.sitp.ac.cn

‡luwei@mail.sitp.ac.cn

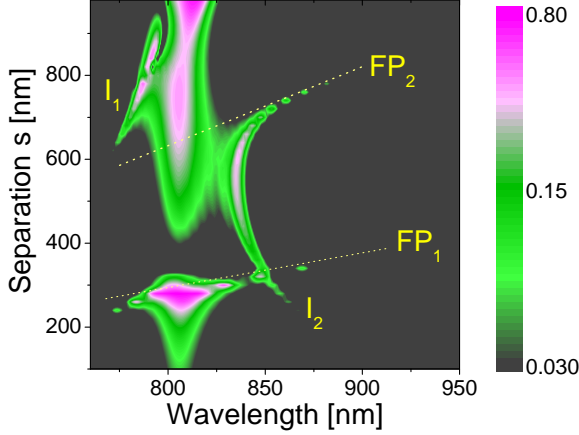


FIG. 1: (color online). The transmission spectrum as a function of the layer separation s . The two dashed lines mark the Fabry-Pérot-like resonances mainly determined by s . I_1 and I_2 indicate two additional channels induced by the interaction between the localized plasmon polaritons on the metal films.

To obtain $\cos(\alpha + \varphi) = -1$, the separation s must satisfy

$$n_1 s = \left[n - \frac{1}{2} - \frac{\alpha(\lambda)}{2\pi} \right] \lambda. \quad (3)$$

Further assuming the phase $\alpha(\lambda)$ is almost constant in the wavelength region of interest, the separation s consequently is proportional to the wavelength λ . Because this mechanism is mainly determined by the separation s and similar to the resonant mechanisms of the Fabry-Pérot (FP) cavities, we therefore denote it as FP resonance. It should be mentioned that the derivative $ds/d\lambda$ of different order resonance relates to the integer n and therefore has different value.

The freestanding bilayered structured metal films studied consists of two identical 500-nm-thick silver films, each film is further perforated by an array of square cross-section holes. The array period and hole side length are fixed to be 750 nm and 280 nm, respectively. These two perforated silver films are separated by vacuum with a variable separation s . The relative dielectric constant of silver is fitted by the Drude model of

$$\epsilon(\omega) = 1.0 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}, \quad (4)$$

where $\omega_p = 1.374 \times 10^{16} \text{ s}^{-1}$ is the bulk plasma frequency determined by the density of conduction electrons, $\gamma = 3.21 \times 10^{13} \text{ s}^{-1}$ represents the phenomenological damping rate [24]. A similar single-layer silver film was numerically studied earlier at normal incidence, and a peak around 802-nm wavelength was observed in the transmission spectrum [17, 25].

Our main result is shown in Fig.1, where the effect of the layer separation s on the transmission spectrum of the

bilayered structure under normal incidence is calculated with the aid of a three-dimensional finite-difference time-domain approach [26]. We are interesting in the wavelength region [750, 950] nm where the far-field diffractions are prohibited at normal incidence because the wavelength is bigger than the array period. Multiple transmission peaks occur by increasing the s from 100 nm to 980 nm with an increment of 20 nm, and three important properties can be observed.

First, the subwavelength patterned metal films can be conceptually simplified to the idealized bilayered slabs studied earlier by approximating each perforated film as a homogeneous medium with an effective permittivity. Consequently physical mechanisms including direct tunnelling and FP resonances are reproduced to a certain degree. More specifically, the bright column around 802-nm wavelength is due to the direct tunnelling, and an example of the electric-field distribution is shown in Fig.(2a). On the other hand, the two inclined lines (marked as FP_1 and FP_2 respectively) with different slopes are induced by the first-order and second-order FP resonances, respectively, and their typical electric-field distributions are plotted in Fig.(2c,2d). Evidently, as the general characteristics of the FP resonances, different-order standing waves are formed between the metal films.

Second, the strong overlap or/and repulsion between LPPs around two metal films lifts up the original degenerate state (corresponding to $s \rightarrow \infty$ therefore no LPPs interaction), and results in two additional states for efficient light transmission [25]. Typical electric-field distributions correspond to the higher-energy (I_1 in Fig.1) and lower-energy (I_2 in Fig.1) states are shown in Fig.(2e) and Fig.(2f), respectively. Evidently, the higher (lower)-energy state sits on the left (right)-hand side of the original 802-nm peak, and the corresponding wavelength should monotonically increase (decrease) with increasing the film separation s (therefore decreasing the LPPs interaction). Moreover, the LPPs interaction is so weak for s bigger than 900 nm that these two states almost coincide with the original 802-nm peak and hence lead to an enhanced transmission. On the other hand, anti-crossing between the second-order FP (FP_2) resonance and the (I_2) state happens around a separation of 600 nm. It is possibly induced by the fact that their modes greatly resemble each other [27].

Third, the separation s influences the direct tunnelling mechanism remarkably in the near-field region ($s < 400$ nm). The transmission intensity first increases steeply from almost zero at $s = 100$ nm to roughly 80% at $s = 280$ nm (the corresponding electric-field distribution is plotted in Fig.(2b)), then drops to zero at $s = 340$ nm again. Although the FP effects may contribute somewhat to this rapid variation by tuning the \cos term in Eqs.(2), the dominant mechanism is believed to be the strong overlap between the near-field LPPs around two metal films. The LPPs overlap constructively enhancing the transmission in the region $s < 280$ nm, while destructively blocking the light propagation around $s = 340$ nm.

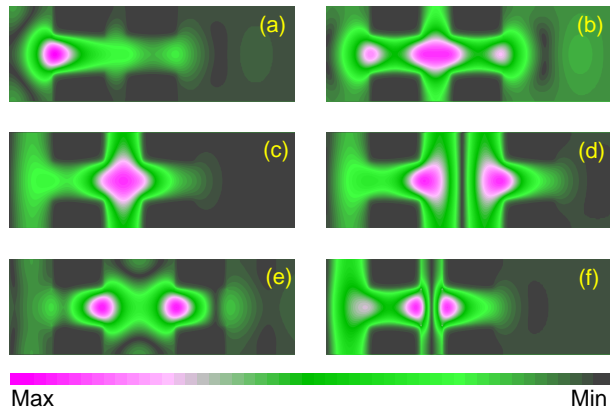


FIG. 2: (color online). The distribution of electric field amplitude corresponds to different mechanisms (see the context), at cross section (along the light propagation direction) with different separation s . (a) The direct tunnelling with $s = 200$ nm; (b) The direct tunnelling with $s = 280$ nm; (c) The first-order Fabry-Pérot resonance (FP_1 in Fig.1) with $s = 350$ nm; (d) The second-order Fabry-Pérot resonance (FP_2 in Fig.1) with $s = 780$ nm; (e) The higher-energy channel (I_1 in Fig.1) with $s = 660$ nm; (f) The lower-energy channel (I_2 in Fig.1) with $s = 200$ nm.

Since the overlap is exponentially decreasing with the increase of the layer separation, its influence is quite weak for bigger s and the transmission intensity hence varies smoothly.

To close the discussion, we connect our present result with the previous studies. It should be emphasized that quite similar layer-separation-transmission dependence was experimentally observed in the terahertz (THz) region, and the mechanisms including both the direct tunnelling and the FP resonances were found [28]. Another experiment regarding a cascaded structured metal

films sandwiched a dielectric (vacuum in our study) layer stressed the contributions of the FP resonance and the LPPs coupling [29]. Nanostructured silver multilayers were also experimentally investigated and the multiple scattering, the complicated counterpart of the FP resonance, were found to influence the optical transmission significantly [30]. Few studies concentrated on the lateral displacement between the subwavelength hole arrays in different metal films. Because the LPPs overlap (interaction) is sensitive to the lateral displacement, similar to their dependence on the vertical separation s studied here, the two additional states (I_1 and I_2) and even the direct tunnelling can be therefore tuned by the lateral displacement in the near-field region (small s) [28, 31].

In summary, we studied the efficient transmission of electromagnetic wave through subwavelength hole arrays in bilayered metal thin films by varying the layer separation. Multiple transmission maximums were observed, and the underlying physical mechanisms were exploited by comparing the subwavelength patterned structure with an idealized bilayered dielectric slabs. The near-field localized plasmon polaritons at the metal films were found not only to modify the direct tunnelling (in constructive or destructive way) significantly, but also their interaction (overlap) form two additional channels for transmitting the light energy efficiently.

We thank Dr. Colm Dineen for improving the writing. This work is partially supported by multiple grants from the State Key Program for Basic Research of China (2007CB613206, 2006CB921704), National Natural Science Foundation of China (10725418, 10734090 and 60576068), Key Fund of Shanghai Science and Technology Foundation(08JC14 21100), and Knowledge Innovation Program of the Chinese Academy of Sciences. Computational resources from the Shanghai Super-computer Center are acknowledged.

-
- [1] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, P. A. Wolff, "Extraordinary optical transmission through sub-wavelength hole arrays," *Nature* 391, 667(1998).
 - [2] H. A. Bethe, "Theory of Diffraction by Small Holes," *Phys. Rev.* 66, 163 (1944).
 - [3] H. J. Lezec and T. Thio, "Diffracted evanescent wave model for enhanced and suppressed optical transmission through subwavelength hole arrays," *Opt. Express* 12, 3629 (2004).
 - [4] N. García and M. Bai, "Theory of transmission of light by sub-wavelength cylindrical holes in metallic films," *Opt. Express* 14, 10028 (2006).
 - [5] N. García and M. Nieto-Vesperinas, "Theory of electromagnetic wave transmission through metallic gratings of subwavelength slits," *J. Opt. A: Pure Appl. Opt.* 9, 490 (2007).
 - [6] T. Matsui, A. Agrawal, A. Nahata, and Z. V. Vardeny, "Transmission resonances through aperiodic arrays of subwavelength apertures," *Nature* 446, 517 (2007).
 - [7] L. Martin-Moreno, F. J. Garcia-cidal, H. J. Lezec, K. M. Pellerin, T. Thio, J. B. Pendry, and T. W. Ebbesen, "Theory of extraordinary optical transmission through sub-wavelength hole arrays," *Phys. Rev. Lett.* 86, 1114 (2001).
 - [8] K. L. van der Molen, K. J. K. Koerkamp, S. Enoch, F. B. Segerink, N. F. van Hulst, L. Kuipers, "Role of shape and localized resonance in extraordinary transmission through periodic arrays of subwavelength holes: experiment and theory," *Phys. Rev. B* 72, 045421 (2005).
 - [9] W. L. Barnes, W. A. Murray, J. Dintinger, E. Devaux, T. W. Ebbesen, "Surface plasmon polaritons and their role in the enhanced transmission of light through periodic arrays of subwavelength holes in a metal film," *Phys. Rev. Lett.* 92, 107401 (2004).
 - [10] Y. Bao, R. Peng, D. Shu, M. Wang, X. Lu, J. Shao, W. Lu, N. Ming, "Role of Interference between Localized and

- Propagating Surface Waves on the Extraordinary Optical Transmission Through a Subwavelength-Aperture Array,” *Phys. Rev. Lett.* 101, 087401 (2008).
- [11] L. Salomon, F. Grillot, A. V. Zayats, F. de Fornel, “Near-field distribution of optical transmission of periodic subwavelength holes in a metal film,” *Phys. Rev. Lett.* 86, 1110(2001).
 - [12] J. B. Pendry, L. Martin-Moreno, F. J. Garcia-Vidal, “Mimicking surface plasmons with structured surfaces,” *Science* 305, 847(2004).
 - [13] K. J. Webb, J. Li, “Analysis of transmission through small apertures in conducting films,” *Phys. Rev. B* 73, 033401 (2006).
 - [14] H. F. Ghaemi, T. Thio, D. E. Grupp, T. W. Ebbesen, and H. J. Lezec, “Surface plasmons enhance optical transmission through subwavelength holes,” *Phys. Rev. B* 58, 6779 (1998).
 - [15] P. Lalanne, C. Sauvan, J. P. Hugonin, J. C. Rodier, P. Chavel, “Perturbative approach for surface plasmon effects on flat interfaces periodically corrugated by subwavelength apertures,” *Phys. Rev. B* 68, 125404 (2003).
 - [16] E. Popov, M. Neviere, S. Enoch, R. Reinisch, “Theory of light transmission through subwavelength periodic hole arrays,” *Phys. Rev. B* 62, 16100, (2000).
 - [17] Y. Zeng, Y. Fu, X. Chen, W. Lu, and H. Ågren, “Selective excitation of surface-polariton Bloch waves for efficient transmission of light through a subwavelength hole array in a thin metal film,” *Phys. Rev. B* 76, 035427 (2007).
 - [18] R. Müller, V. Malyarchuk, and C. Lienau, “Three-dimensional theory on light-induced near-field dynamics in a metal film with a periodic array of nanoholes,” *Phys. Rev. B* 68, 205415 (2003).
 - [19] H. Shin, P. B. Catrysse, S. Fan, “Effect of the plasmonic dispersion relation on the transmission properties of subwavelength cylindrical holes,” *Phys. Rev. B* 72, 085436(2005).
 - [20] S. A. Darmanyan, A. V. Zayats, “Light tunneling via resonant surface plasmon polariton states and the enhanced transmission of periodically nanostructures metal films: an analytical study,” *Phys. Rev. B* 67, 035424 (2003).
 - [21] F. I. Baida, D. V. Labeke, “Three-dimensional structures for enhanced transmission through a metallic film: annular aperture arrays,” *Phys. Rev. B* 67, 155314 (2003).
 - [22] Z. Ruan, M. Qiu, “Enhanced transmission through periodic arrays of subwavelength holes: the role of localized waveguide resonance,” *Phys. Rev. Lett.* 96, 233901 (2006).
 - [23] A. V. Zayats, I. I. Smolyaninov, A. A. Maradudin, “Nano-optics of surface plasmon polaritons,” *Phys. Reports* 408, 131 (2005).
 - [24] *Handbook of optical constants of solids*, edited by E. D. Palik (Academic, Orlando, 1985).
 - [25] Y. Zeng, Y. Fu, X. Chen, W. Lu, H. Ågren, “Dynamics of the damping oscillator formed by the collective generation of surface polaritons for extraordinary light transmission through subwavelength hole arrays in thin metal films,” *Phys. Rev. B* 76, 125409 (2007).
 - [26] A. Taflov and S. C. Hagness, *Computational Electrodynamics: the finite-difference time-domain method*, Second Edition, Artech House Boston 2000.
 - [27] J. J. Sakurai, *Modern Quantum Mechanics*, Revised Edition, Addison-Wesley 1994.
 - [28] F. Miyamaru, M. Hangyo, “Anomalous terahertz transmission through double-layer metal hole arrays by coupling of surface plasmon polaritons,” *Phys. Rev. B* 71, 165408 (2005).
 - [29] Y. Ye, J. Zhang, “Enhanced light transmission through cascaded metal films perforated with periodic hole arrays,” *Opt. Lett.* 30, 1521 (2005).
 - [30] Z. H. Tang, R. W. Peng, Z. Wang, X. Wu, Y. J. Bao, Q. J. Wang, Z. J. Zhang, W. H. Sun, M. Wang, “Coupling of surface plasmons in nanostructured metal/dielectric multilayers with subwavelength hole arrays,” *Phys. Rev. B* 76, 195405 (2007).
 - [31] M. He, L. Wang, J. Liu, X. Zhai, Q. Wan, X. Chen, B. Zou, “Controllable light transmission through cascaded metal films perforated with periodic hole arrays,” *Appl. Phys. Lett.* 93, 221909 (2008).